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Mass Limit on a Positively Charged Heavy Muon*

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We report a preliminary search for a positively charged lepton (Y^+) coupled directly to the μ^- and ν_μ (i.e., muon number = +1). Using the production process $\nu_\mu + N \rightarrow Y^+ + \text{anything}$, we have looked for the μ^+ from the decay $Y^+ \rightarrow \mu^+ + \nu_\mu + \nu_\mu$. The expected number of μ^+ events is given as a function of the heavy-lepton mass, the branching fraction to muons, and the heavy-lepton coupling. For typical gauge-theory predictions, we obtain the 90% confidence limit $M_Y > 2 \text{ GeV}/c^2$.

One striking feature of weak interactions is the small number of members observed in the known lepton families. For example, the muon family presently contains only two observed members: ν_μ and μ^- . It is important to search for higher-mass members, whose existence could have profound implications.

Considerable theoretical work^{1,2} in the past few years has focused on unified gauge theories to predict controlled high-energy behavior for the weak interactions and to unify the theoretical treatment of weak and electromagnetic interactions. Theories suggested thus far contain massive charged intermediate vector bosons ($M_w \sim 40 \text{ GeV}/c^2$) together with neutral weak currents and/or heavy leptons. The suggested heavy leptons have the following properties: (1) They belong to existing lepton families (either electron or muon), and (2) they have different electric charge from existing charged leptons of the same lepton number.

The phenomenology of the proposed particles has been discussed at length by Bjorken and Llewellyn-Smith (BLS)³ and by Llewellyn-Smith.⁴ These authors mention several ways of searching for massive leptons. To date, we know that any

heavy lepton must have a mass greater than that of the K meson. Some calculations^{3,5} have indicated that, were a positive heavy muon to exist with mass less than $1 \text{ GeV}/c^2$, it might have been observed in the CERN neutrino data.⁶

We emphasize here the production of heavy muons (Y^+), in a beam of high-energy muon neutrinos. The ordinary mode of interaction for neutrinos of high energy is

$$\nu_\mu + N \rightarrow \mu^- + \text{hadrons.} \quad (1)$$

The conjectured Y^+ would be produced by the process

$$\nu_\mu + N \rightarrow Y^+ + \text{hadrons.} \quad (2)$$

Reaction (1) has been observed and measured at CERN⁶ with neutrinos of energy $E_\nu \approx 1\text{--}10 \text{ GeV}$. The results are consistent with neutrino scattering from spin- $\frac{1}{2}$ fractionally charged pointlike constituents (quarks), with predominantly $V-A$ coupling (mainly scattering off quarks rather than antiquarks).⁷ Preliminary National Accelerator Laboratory data are also qualitatively consistent with this picture at higher energies.^{8,9}

In the quark model, the differential cross section for either (1) or (2) is given by

$$\frac{d^2\sigma_\pm}{dx dy} = \frac{g_\pm^2 s}{\pi(sx + M_w^2)^2} \left[2xf(x) \left(1 - \frac{m_\pm^2}{sx} \right) + 2x\bar{f}(x)(1-y) \left(1 - y - \frac{m_\pm^2}{sx} \right) \right], \quad (3)$$

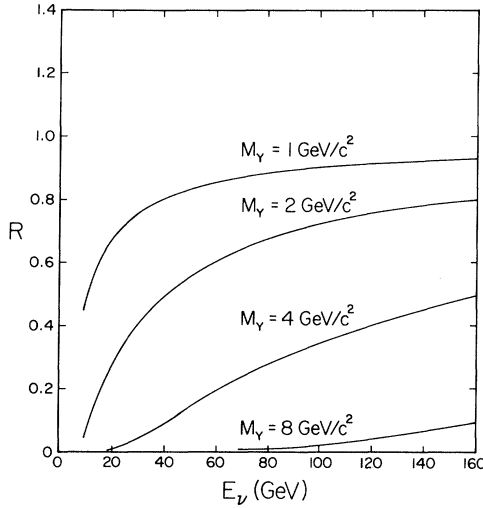


FIG. 1. Ratio of Y^+ production to μ^- production in a beam of muon neutrinos of energy E_ν . The quark-meson model structure function relationships are assumed.

where g_+ (g_-) is the coupling of the Y^+ (μ^-) to the muon neutrino; s is the square of the center-of-mass energy; M_w is the mass of the charged intermediate vector boson (assumed large); x, y are the deep-inelastic variables ($x = Q^2/2M\nu$, $y = \nu/E_\nu$); $2xf$ ($2x\bar{f}$) is the momentum distribution for quarks (antiquarks) in the nucleon (related to the deep-inelastic structure functions); and m_+ (m_-) is the mass of the Y^+ (μ^-). Figure 1 shows the ratio of total cross sections expected for Reactions (2) and (1), obtained by integrating Eq. (3) over the available phase space, and assuming that $g_+^2 = g_-^2$. For this calculation, we have taken $xf(x) \propto F_2(x)^{ed}$, i.e., the scaling structure function found in inelastic electron-deuteron scattering,¹⁰ and $\bar{f}(x) = 0$. Inclusion of the small antiquark component⁷ implied by the low-energy CERN neutrino data changes Fig. 1 by a negligible amount. The calculation also assumes that $M_w^2 \gg s$.

The decay modes expected for the Y^+ are

$$Y^+ \rightarrow \nu_\mu + \mu^+ + \nu_\mu, \quad (4)$$

$$Y^+ \rightarrow \nu_\mu + e^+ + \nu_e, \quad (5)$$

$$Y^+ \rightarrow \nu_\mu + \text{hadrons}. \quad (6)$$

The search described here is for μ^+ from the decay (4). If these are the only modes available, it has been estimated that³

$$B \equiv \Gamma(Y^+ \rightarrow \nu_\mu + \mu^+ + \nu_\mu) / \Gamma(Y^+ \rightarrow \text{anything}) \approx 0.3$$

for $1 < M_Y < 6 \text{ GeV}/c^2$. However, if there exists an uncharged heavy muon, Y^0 , which is lighter

than the Y^+ , other decays of the type $Y^+ \rightarrow Y^0 + \text{anything}$ might be expected. The exact contribution is somewhat model- and mass-dependent, though phase-space considerations alone should make such decay rates small in comparison to (4), (5), and (6).

In our experiment, a narrow-band, sign-selected beam of positive pions and kaons, of mean energy 160 GeV, was allowed to decay to neutrinos ($\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $K^+ \rightarrow \mu^+ + \nu_\mu$). The forward neutrinos entered our apparatus, giving two bands of neutrino energy: from K decay, $\langle E_\nu \rangle \approx 145 \text{ GeV}$; from π decay, $\langle E_\nu \rangle \approx 50 \text{ GeV}$. This run has been described previously¹¹ in a communication describing a search for the charged intermediate boson. The same data, consisting of 112 reconstructed neutrino interactions, are used in the present paper. For this search, the sign-selected nature of the beam is of prime importance. The only reaction that might be expected to produce a background μ^+ in our sample is

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \text{hadrons} \quad (7)$$

from background π^- or K^- decays.

The run reported here consisted of 2.65×10^{16} protons on target. Of the 112 events inside the fiducial volume which could be reconstructed kinematically, 111 had a definite μ^- secondary. Subsequent analysis⁸ showed that these events are consistent with production from Reaction (1), assuming quark-model structure functions.

There existed in this run a single μ^+ event with observed hadron energy $E_h \approx 2 \text{ GeV}$, muon energy $E' = 57 \text{ GeV}$, and muon angle $\theta' = 34 \text{ mrad}$. If this event corresponded to decay of a Y^+ , its mass would be several GeV/c^2 . However, we believe that this event comes from $\bar{\nu}_\mu$ contamination (7) for the following reasons:

(1) Independent background runs demonstrated the existence of wide-band antineutrino background at roughly the one-event level.

(2) This event has small hadron energy. This is more characteristic of $\bar{\nu}$ interactions than of heavy-lepton production. Figure 2 shows the fraction of μ^+ events expected, for both cases, in which the ratio (y) of observed hadron energy to observed total energy is less than y_μ . The curves include the apparatus acceptance, and incorporate the cross section (3). The observed event had $y = 0.03$. About 1% of Y^+ decays might be expected to have $y \leq 0.03$, while about 20% of $\bar{\nu}$ interactions are expected with $y \leq 0.03$. This occurs principally because the secondary μ^+ in $\bar{\nu}_\mu$ interactions takes a large fraction of the en-

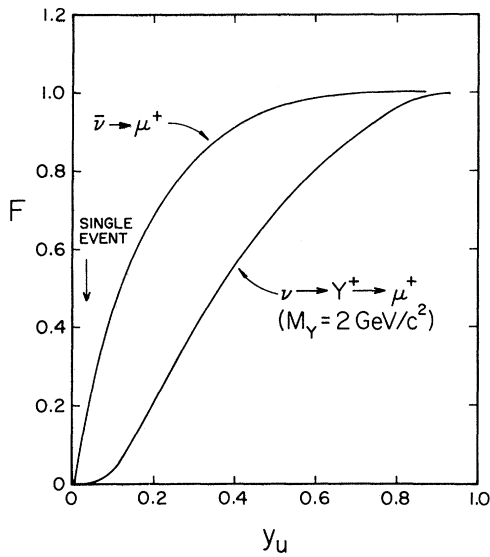


FIG. 2. The calculated fraction, F , of events in our apparatus with $y < y_u$, where $y = E_h/E_{\text{tot}}$. The curves correspond to the reactions

$$\begin{aligned} \nu + N &\rightarrow Y^+ + \text{anything}, \\ &\quad \downarrow \\ &\mu^+ + \nu_\mu + \nu_\mu \end{aligned}$$

and

$$\bar{\nu} + N \rightarrow \mu^+ + \text{anything}.$$

Quark-model structure functions are assumed. The single observed μ^+ event is indicated.

ergy,⁷ while the μ^+ from the predominantly left-handed Y^+ has low laboratory energy. We conclude that this anomalous event is most likely from $\bar{\nu}_\mu$ contamination.

To calculate our sensitivity, we have used a Monte Carlo calculation which assumes the cross section (3), and takes into account the polarization of the Y^+ and subsequent decay angular distribution via Reaction (4). Figure 3 shows $N(g_-/g_+)^2(0.3/B)$, where N is the number of μ^+ events expected in this run, as a function of heavy lepton mass, M_Y . For simple gauge theories, we have $g_+^2 = g_-^2$, and for specific assumptions for the decay probability,³ we have $B \approx 0.3$. With these assumptions, the ordinate corresponds to the expected number of events in the experiment. The one-event level is in the region of $M_Y \sim 5$ GeV/c^2 . The Poisson probability for observing one event when the mean is 3.56 is equal to 0.1. We can therefore quote a lower mass bound on a Y^+ as $M_Y > 2$ GeV/c^2 , with 90% confidence. For differing assumptions regarding the lepton coupling or branching ratio, the limit can be adjusted.

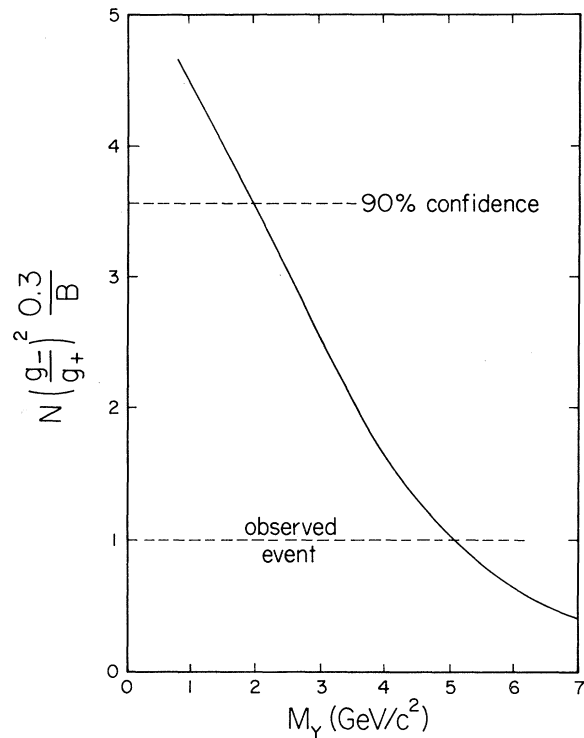


FIG. 3. $N(g_-/g_+)^2(0.3/B)$ as a function of heavy lepton mass, M_Y . N is the expected number of μ^+ events in the experiment, B is the branching ratio for $Y^+ \rightarrow \nu_\mu + \mu^+ + \nu_\mu$, and g_+ (g_-) is the weak coupling of the heavy lepton (muon) to the neutrino and the weak current.

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Inclusive π^- Distributions from 205-GeV/c pp Interactions*

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Inclusive π^- distributions from 205-GeV/c pp interactions, covering the full range of longitudinal and transverse momenta, have been obtained using the 30-in. hydrogen bubble chamber at the National Accelerator Laboratory. These data provide new evidence for scaling in the fragmentation region and for a plateau in the central region of rapidity. The 90°-c.m. invariant cross section varies as $\exp[-(10 \pm 2)P_T^2]$ in the range $P_T^2 \leq 0.1$ (GeV/c)².

In this Letter, we report on a measurement of the single-particle inclusive distribution for the reaction $pp \rightarrow \pi^- + \text{anything}$ at 205 GeV/c. This measurement covers the entire range in both the center-of-mass longitudinal (P_L^*) and transverse (P_T) momenta. This is also the highest energy at which a single experiment covering the entire range of these variables has been reported. Similar data^{1,2} have been reported from the CERN intersecting storage rings (ISR). These ISR experiments cover various restricted intervals of P_L^* and P_T , at energies corresponding to laboratory momenta between 225 and 1500 GeV/c.

Our data were obtained from approximately 17 000 pictures taken with the 30-in. hydrogen bubble chamber exposed to a 205-GeV/c proton beam at the National Accelerator Laboratory (NAL). The results reported here are confined to negative-particle production. Ordinarily, the measurement of momenta and angles of secondary

tracks in a bubble chamber is a routine matter. However, for this high beam momentum and for high-multiplicity events, there are practical complications involving track matching in the different stereoscopic views, overlapping track images, and poor momentum determination for fast forward-going secondaries. To determine how these complications might affect our data, we have made two independent sets of measurements, using somewhat different experimental methods.

Following the scan³ of the film, a fiducial volume was selected that yielded a 20-cm minimum track length for outgoing tracks. For the first measurement method, each view was examined at high magnification (6 times life size), and the spatial pattern of the bubbles was used to match all secondary tracks. The event was then measured in two views and spatially reconstructed using TVGP. For the second method, a minimum-sagitta criterion was used to determine which